Chapter 8
A Recommended Procedure and Best Practices for MIMO Vibration Testing

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Abstract Test teams must follow several steps to meet vibration test objectives, such as matching the desired specification and delivering quality data. These steps include test setup, pre-test troubleshooting and verification, test execution, data analysis, and documentation. With multiple-input/multiple-output (MIMO) vibration testing growing in popularity, a MIMO-specific testing procedure and recommended best practices is needed to help test teams and their customers set expectations and ensure high-quality, reliable test outcomes. Though vibration testing is well established with good recommended best practices available in standards and procedures from various test laboratories, there is less available for MIMO vibration and what is available may not be in common use.

Sandia National Laboratories (SNL) is pushing to develop and adopt a MIMO vibration testing procedure and disseminate best practices as the use of MIMO grows for both research and customer-facing test work. This paper aims to be a supplement to existing MIMO testing guidance in MIL810 Method 527 based our own needs and experience [1]. We present a procedure that is applicable to random vibration and transient vibration test methods. Example test setups and procedures will be given along with recommended best practices.

Keywords MIMO · Random vibration · Transient vibration · Vibration testing · Procedure · best practices

Introduction

A test procedure is useful for many reasons, including standardizing work, improving quality, and making it easier for test engineers and operators to complete test programs. Even though MIMO vibration testing is still in the research and development phase for some uses or test laboratories, a MIMO-specific testing procedure is still useful. At SNL, we are developing new MIMO test techniques and putting them to work in a rapid research-development-application sequence. On the one hand, this makes it difficult to have a standard procedure or workflow as almost no test is the same as the last. On the other hand, the demand for MIMO tests is increasing, requiring more tests and more staff to run those tests. Having some procedure to use to train these staff and standardize aspects of the MIMO testing workflow is valuable, even at this stage of MIMO test adoption.

Brief Overview of MIMO Vibration Testing

The purpose of vibration testing is to subject test hardware to vibration environments that may be encountered in-service to verify the adequacy of the design or test functional performance. Vibration testing is also used to generate test-based structural dynamics models and generate model validation data in relevant vibration conditions. MIMO vibration tests provide various benefits for each of these use cases, but the main benefit is that in-service environments are typically multi-axial and as a result a MIMO test is needed to accurately recreate the in-service environment. Outputs of a MIMO vibration test are dynamic response data, often in the form of acceleration responses from gauges installed on the test hardware, and functional performance or survivability during and after the vibration test. As a result, obtaining high-quality vibration response data and performing a test that is within specifications is critical.

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Types of MIMO Vibration Tests

There are two main classes of MIMO vibration tests: base excitation and multi-shaker excitation. In a base excitation test, commonly called a 6DOF test, the test hardware is mounted to the table of a 6DOF vibration test machine via fixturing and shakers excite the table to create a multi-axial vibration environment for the table and attached parts. Fig. 1 shows an example 6DOF setup with a test article mounted to a large 6DOF test machine via a fixture.

In a multi-shaker test, sometimes called an impedance-matched multi-axis test (IMMAT test), the test hardware is directly connected to several small shakers which work together to excite the system [2, 3]. Fig. 2 shows an example multi-shaker or IMMAT test setup where several small modal shakers are directly attached to a large test article. A fixture is attached to the test article to simulate the in-service attachment impedance and boundary condition.

Fig. 1 Example 6DOF test setup

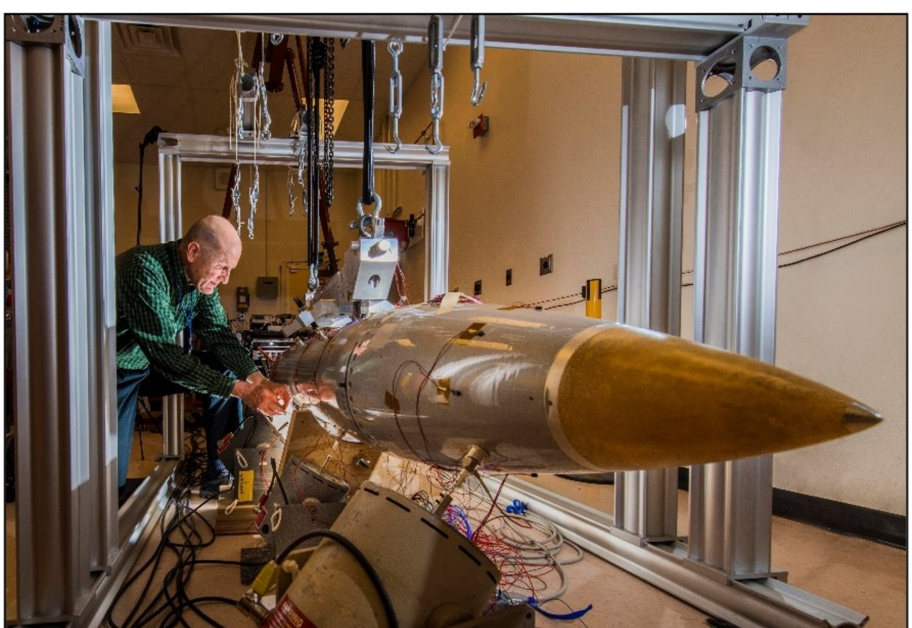

Fig. 2 Example multi-shaker or IMMAT test setup

For either setup, a MIMO vibration control system reads the accelerometer response of the 6DOF table or test hardware and determines how the shakers need to be driven to create a response which matches the test specifications. MIMO vibration specifications are typically written at multiple locations and/or directions, defining the complicated, multi-axial vibration conditions that are observed in-service.

General Testing Process

The basic test process is as follows:

1. The test provider receives a test request from the customer. All stakeholders meet to define the MIMO test type and test article configuration.
2. Perform the initial test set-up and troubleshooting to install the test article on the 6DOF machine or in the IMMAT test set-up.
3. Perform system identification testing and standard data quality evaluations (coherence, kurtosis, etc.).
4. Perform pre-test predictions to determine the optimal controller settings.
5. Perform the vibration test and process the resulting data.
6. Review the test data and report the test results to the stakeholders.
7. Archive the all the test data and reports to close-out the test.

The Need for a Procedure

While each test is different in terms of test hardware, setup, instrumentation, environments, and goals, much of what makes for a good test is common. This includes thorough and thoughtful test planning and design, work planning and review, test execution, data post-processing and test close out. This MIMO vibration testing procedure lists out these steps in moderate detail, including what should be done at each step to ensure a test is well planned, thoroughly documented, properly executed, and provides reliable data. When completed per the procedure, the test should meet the customer's goals.

This process was developed with the acknowledgement that MIMO is relatively new, so techniques and best practices will change as the field matures. However, it is important to have a standard procedure we can follow for each test to ensure consistent practices and quality outcomes.

The procedure begins with initial test definition, which is used to roughly define the goals and approach that should be used for the test. This is then refined in a thorough test design phase, where all the details of the test process and physical setup are defined. The hands-on portion of testing begins with the test setup phase, which includes hardware and data acquisition setup, instrumentation, and documenting the test setup. Next, the test can be run, which follows the test plan and entails troubleshooting, system characterization, and the actual vibration tests. Checkpoints are inserted between runs to verify data quality, check test results, and make controller or setup changes. The last step is to close-out the test by completing documentation and archiving data. This document is written in roughly chronological order, so the readers can follow it step by step as they progress through the MIMO testing workflow. That said, much like following a recipe, it is important to read then entire procedure and understand each step before beginning. A selection of recommended best practices is included at the end.

Initial Test Definition

Test activities begin with initial conversations between the customers (hardware owners needing a test) and the test engineers (those designing and performing the test) and any other stakeholders. These conversations should begin to define the test in terms of budget, schedule, hardware, test method, specifications, requirements and data products. The goals of these initial consultation meetings are to understand customer needs, requirements, desired outcomes, and how that may (or may not) connect to what a MIMO test can provide.

With test goals and requirements understood, the test team should meet to begin preliminary test definition. The following questions should be addressed in preliminary test definition:

- Is MIMO a good test methodology for this customer's test goals?
- What setup and test approach is appropriate? 6DOF machine, frame-based 6DOF, IMMAT, etc.?
- Resources: are there staff available to support this? Is there lab space and test equipment available?

- Are there pre-existing specifications or are data available to derive specifications available?
- Is modeling and simulation support needed for pre-test design?
- What custom hardware or additional equipment is needed?
- Who should be on the test team and what are the roles and responsibilities for all the members of the team. It is critical that a test lead be identified in this step.

With those questions answered, the test team should write up the proposed test definition and review it with the customer, making any necessary changes.

Resource Allocation

Next, the test lead should meet with lab owners, the test team, and other support personnel to discuss the schedule, budget, lab space, and equipment to ensure there are the resources needed, at the right time, to complete the test activities. It is the test lead's job to manage risks, including schedule, budget, space and equipment, to ensure the test is completed in the desired time frame and meets customer goals.

Test Requirements

Test requirements must be discussed and negotiated between the test lead and the customer as all test design and test execution activities are done to meet test requirements. Though not all requirements are top of mind for all customers, each of these should be discussed so the test lead and customer agree on the purpose of the test, the expected outcomes, and the reports and data products.

Requirements will vary from test-to-test but may include:

- The high-level goals of the test and how those connect to test data products (e.g., the test is for functional performance of a component in a vibration environment, so the goal of the test is to accurately create the vibration environment and function the component during vibration)
- Test hardware and boundary conditions (e.g., test a mass mock using a 6DOF base input)
- Test levels and durations (e.g., test to 0 dB of a P95/50 reentry random vibration specification for 60 seconds)
- Test specifications and tolerances (e.g., multi-axis random vibration profiles from 30 to 4000 Hz with a +/- 6dB tolerance on the specification PSD)
- Do not over-test in terms of duration or level (e.g., one run at full level)
- Collect time history data for all accelerometer channels for all full-level runs and select low-level and system ID runs
- Perform system ID tests pre- and post-full level runs
- Process test data into relevant QOIs and verify data quality for all runs
- Compare test results vs. specifications to verify the test is within tolerance and document any channels or frequency bands out of tolerance
- Document test activities including a complete test geometry, channel table, run log, photos and quick look report

Note that even though the test requirements are defined by a small subset of the stakeholders, everyone involved in the test should have a general familiarity with the test requirements.

Test Design

With the initial test definition completed and agreed upon by the test team and stakeholders, the next step is the development of a detailed test design. Test design encompasses several aspects of testing: test requirements, the list of tests to be run, test specifications, the physical test setup (fixtures, boundary conditions, shaker and accelerometer locations) and pre-test predictions (if possible). Thoughtful and thorough test design is necessary to ensure test objectives can be met within test equipment limitations and the test series can be completed as quickly and smoothly as possible.

Create the Test Matrix and Test Plan

The test matrix and test plan are critical to ensuring that the right tests are run to meet customer needs and to ensure the test hardware isn't over- or under-tested. Typically, the test plan is a document detailing the test hardware, test method, specifications and requirements. The test matrix is the list of tests or runs which are required to meet test requirements and should be created by the test lead and agreed upon by the test team and customer.

A typical MIMO test matrix includes setup and troubleshooting runs (like noise floor and rigid body checks), system ID runs at various levels, low-level tests, full-level tests, and a post-test system ID run. The test matrix should include each test to be run, in the expected order, and include details such as the test level, frequency range, specification, and other useful information such as settings or control methods to use. Any run where data is collected should be planned and put in the test matrix. Deviations from the test matrix should be documented.

The test matrix should also include gates or stopping points to ensure that the group is ready to move forward (i.e., after the system ID and rigid body checks). These may involve thorough data quality reviews or test vs. specification comparisons after key runs. An example test matrix is provided in Appendix A.

Potential Anomalies and Go/No-Go Parameters

In the test plan, list out what could go wrong in the test and develop a procedure about how the expected anomalies should be handled. Attempt to define go and no-go parameters so the test facility can operate as efficiently as possible. Example anomalies could include poor data quality, degraded coherence, failures of critical gauges, test control issues, notable audible responses like rattles or bangs, clear system dynamic changes, or problems with the test article.

Define and Derive Test Specifications

Test specifications are essential to connecting the test results to in-service environments and should be carefully considered during pre-test planning. The test lead should work with the customer and environments engineers to define appropriate, MIMO-compatible specifications for each test. This should be done as early as possible as it may take time to obtain the source data and perform data processing needed to derive specifications. In addition to specifications, test tolerances, limits, and quantities of interest should be defined and derived by this team.

The specification derivation varies in complexity, depending on the MIMO approach that is being used for the test. A simple example of MIMO is simultaneously running an X, Y, and Z direction single axis test, where typical "straight line" PSD specifications can be used for each direction. A complex example of MIMO would be simultaneously controlling the three-dimensional motion at many response DOFs, where the specification includes the phase and coherence between the DOFs in addition to the PSD response at each DOF. Note that, in general, specifications for a MIMO test are not available in standards like MIL810 and need to be derived test-by-test, so this should not be minimized or left to the last minute.

Design the Test Configuration and Setup: Boundary Conditions, Load Paths, Inputs and Outputs

Aspects of the test setup, including fixtures, boundary conditions, shaker locations and sensor locations, all affect test results. With MIMO tests, especially multi-shaker or frame-based tests, there is a lot of design flexibility and therefore a lot to design. The test team should consider and design each aspect of the test setup, ideally with the help of structural dynamics models. Several aspects of the test setup design can be counterintuitive, at least at this point in our collective experience, so basic engineering judgement may not suffice.

For all forms of MIMO tests, the control sensor set must be carefully chosen as the control sensors will affect the response of the rest of the body. In some cases, sensor locations are predetermined based on specification data or pre-existing hardware. General guidance is to have at least as many control DOFs as input DOFs and to have control DOFs well distributed at various locations and directions to cover or observe the entire test article. Having large regions without a control DOF, especially if they have high modal mass, may lead to control problems. In general, more control DOFs lead to more robust vibration control, assuming that the additional control DOFs are not redundant.

For 6DOF tests on the small or large 6DOF machines with built-in tables, a fixture plate and adapters may be needed to go between the 6DOF table and the test article. The fixture plate and adapters should be short, stiff, and light to avoid adding unwanted mass or dynamics to the 6DOF table and to translate the 6DOF motion as completely as possible to the test article.

Frame based tests generally require more elaborate designs and the test team will need to consider the following:

- The general test frame configuration to support the shakers and test article.

- The position, orientation, and quantities of shakers to achieve the desired excitation. It is important to consider the amount of force that is required from each shaker to avoid over-taxing or under-utilizing a specific shaker.
- The test article fixturing and necessary supports.
- How the test stand and fixture dynamics might interact with the test article and influence the control accuracy

For IMMAT setups, use pre-test predictions to determine the number, location, and orientation of shakers needed to meet test requirements. Try to equally load each shaker to avoid over-taxing some shakers and under-utilizing others. Design drive pads which connect the shaker stinger to test article, keeping the drive pads small and light. IMMAT setups also need the test article suspension and boundary conditions to be designed. As the name suggests, the interface impedance should be approximated with a fixture. Dynamic fixture design is notoriously fickle, so again utilize structural dynamics models and predictions in the fixture and general setup design phase.

Custom hardware, including fixtures, adapters, and support structures, should be designed and procured well ahead of the scheduled test date to allow for manufacturing time, dry-fits, and any necessary modifications.

Perform Pre-test Predictions

Early pre-test predictions are useful in test planning for two reasons. First, predictions using structural dynamics models can be used to design the test setup, including fixtures, sensor locations, and shaker locations. Second, once the test configuration is determined, predictions with a structural dynamics model can be used to determine control settings and methods to best balance equipment capabilities (e.g., shaker force) with test outcomes (e.g., meeting accuracy requirements or test levels). These predictions significantly de-risk the test program as changes can easily be made to a model to change fixtures or shaker configurations to design a test that will meet requirements, whereas making these changes later in hardware is often difficult or impossible. If possible, source a model and perform pre-test predictions to make informed test design decisions and understand test performance before any hardware is procured. These models and predictions do not need to be perfect or validated to be useful for test design purposes; use what is available but do not skip this step unless there is known margin in the test setup or a history of adequate performance.

Conduct Test Design Reviews

Once the test design is complete, the test team should conduct design reviews with the customer and peer reviewers to ensure the proposed design will meet test objectives. This review should cover the physical test setup as well as specifications and control approaches. The general test approach should be reviewed as well to ensure the high-level test definition is appropriate.

Test Setup

Test setup begins when test hardware is in-hand and includes building the test frame and test fitting fixtures, gathering instrumentation, data acquisition, and other supplies, installing gauges, and mounting the test article and shakers. Next, the data acquisition system is set up and the data gathering, converting, and archiving methodology is established. Then, photos and notes should be taken to completely document the setup. Once test setup is complete, testing can begin. Note that there is natural overlap with test setup and troubleshooting, so it is reasonable to expect some changes to the test setup after testing begins as the data may indicate something needs to change.

Apply Instrumentation

Instrumentation locations, directions, and labels should be pre-determined in the Test Design phase. Physically installing the instrumentation must be done per the planned instrumentation design and any deviations to gauge locations or directions, as well as any additions or removals must be documented and communicated to the test team and customer. Gauge installation should follow lab best practices to ensure each gauge is securely attached, appropriately isolated, and its cables are cleanly routed. It is important to label each sensor with an ID number and mark the local or global test axes near the sensor to make documenting the sensor's measurement axes as simple as possible.

Once all sensors are installed, document the as-instrumented gauge configuration in the channel table and by building a test geometry, which allow for visualization of each sensor's location and measurement directions. The sensor locations and directions should be compared to specification to ensure that the test setup is compatible with the specification. Subtle errors (such as a polarity flip) in the specification and test setup compatibility can lead to significant control issues in the test.

Install the Test Article

This step varies depending on the test type, but generally entails installing the test article into the test frame or onto the test machine. Specific installation details will be omitted here, but some best practices are to:

- Ensure fixtures or other hardware are securely attached and won't rattle
- Bundle and route cables to strain-relieve gauges and keep the workspace clear
- Label shaker drive cables to ensure the correct drive signal is going to each shaker
- For IMMAT setups, ensure shaker stinger attachments are installed properly and well aligned
- For free-free test setups, check the rigid body mode frequencies to ensure they are sufficiently low
- Document the shaker locations and directions in the channel table and test geometry once test setup is complete

Set up the Data Acquisition and Control System

Carefully connect the gauges and shaker drives to the data acquisition system, following the channel table. Using a two-person team is recommended, with one person plugging in and one person checking or correcting the channel table to match the as-installed sensor configuration. Have both people verify the sensors are plugged into the correct channels before proceeding. Once cable installation is complete, bundle and organize cables to organize the setup and reduce chances of snags or trips.

Define File Naming and Organization Conventions

Data from many tests will be saved during a test series so a simple, common data file naming and file organization convention should be established before testing. A recommended naming convention is to sequentially number the runs and append a short description of the test type, for example:

- run001_noise_floor for a noise floor run at the start of testing (run 1)
- run002_system_id for a system ID test
- run003_random_vibe for a random vibration test after the initial noise floor and system ID runs are complete
- run004_transient for a transient vibration test

Experience has shown that it is not possible to capture all the relevant information for test run in the file name. Consequently, details of each run, including levels, settings, and specifications used would be captured in the run log.

A file structure should be established to organize and store test data files. This may include one or more folders (e.g., organized by day or test type). However it is done, it should be clear and obvious to ensure data is easy to find and access.

The test lead should communicate this naming convention and folder structure to the test team and ensure it is being followed throughout testing.

Document the Test Setup with Photos and Notes

Once the setup is complete, document setup details with photos and notes in the test log. Photos should include the following:

- Several shots of the entire setup taken from various angles and perspectives around the setup (show the entire setup all the way around)
- Several shots zoomed in to show key details in context such as the system axes, shaker arrangements, cable routing and external instrumentation
- At least one well-posed photo which is taken to showcase the test and be used in slides and reports. This photo should have strong visual impact and be free from visual clutter such as tools, supplies or things in the background

Verify that all photos are clear and in focus. Ensure the entire setup is documented before proceeding.

Notes of the setup should supplement the photos and include details such as the location of shakers and sensors, orientation of the system on the test setup (e.g., system axes) and hardware used such as fixturing and suspension. Notes and photos should be complete enough to allow the test to be recreated in the future.

Test Execution

Test execution begins after test setup is complete and the test team and customer agree testing can proceed. Specific runs will vary test to test, but will generally include the following steps:

- Troubleshooting where the test setup is checked and changed until everything is working properly
- System identification and rigid body tests where low-level inputs are used to characterize the system dynamics and transfer functions and verify the sensor orientations
- Low-level and full-level tests for each environment
- Post-test checks to verify the system state of health after testing is complete

Successful testing is often the product of thorough planning and proper execution, so care must be taken to methodically complete each test in the test matrix, document the results, and verify data quality and test results along the way.

Pre-test Brief

The test lead should coordinate a pre-test brief with the test team, customer, and other stakeholders. This brief should review the test goals, test plan and test matrix, any hazards, and roles during test. The test lead should document when the pre-test brief occurred, who attended, and what was covered.

Follow the Test Matrix and Complete the Run Log

Testing should follow the test matrix step by step. After each test is complete, note the details of the test in the run log and complete the necessary data quality and test comparison checks before proceeding. Tests should not be run in batches (e.g., multiple runs back-to-back) as details from each test can get missed or problems may go unnoticed until the end. Before proceeding to the next test, ensure the test data is properly saved, the run log is complete, and the data and test results are adequate.

At times, there may be additional tests beyond what was planned in the test matrix or test plan. For example, during troubleshooting, there may be a dead sensor which needs to be replaced and verified or during low-level testing some controller settings may need to be modified. These are expected changes and are generally acceptable deviations, though the test lead should oversee and verify any deviations from the test matrix. Additional tests at high or full levels must be approved by the customer and other stakeholders as additional high-level tests may induce damage to the test article. Any deviations from the test matrix should be documented and treated as an informal “change order” to the test.

In many cases, the test run log is the single source of truth for what testing was done, the test settings, and what (if any) anomalies were encountered during the test. As such, it is imperative that the test run log is complete and contains the details of how each test was run, any anomalies that occurred, along with the data and specification file names. The run log should include key controller settings such as control channels, regularization settings, and transformations. All post-processing relies on connecting the data files to the metadata in the run log, so the run log must be complete, clear, and useful. The run log must be filled out after each individual run. At the end of each test day, the test lead should verify the run log is complete and save an archived copy.

Troubleshoot the Test Setup

The first step in testing is troubleshooting the setup, which includes verifying each sensor is reading and each shaker is running. Utilize noise floor and system ID tests to troubleshoot the system and identify and fix problematic sensors or shakers. During troubleshooting and all phases of testing (system ID, low level and full level vibration testing) it is important to listen for rattles or other sources of nonlinearity and identify these issues in the data, for example by checking coherence. Poor coherence in control gauges will result in poor test results, so rattles or loose joints which cause poor coherence should be addressed during troubleshooting and throughout the test.

Run Rigid Body Checks to Verify Instrumentation and Test Geometry

Verify sensor orientation by running rigid body checks on the system. This entails shaking the system in 3 translation and 3 rotation directions (e.g., X, Y, Z, RX, RY, RZ) using a low level, low frequency sinusoidal excitation. With a MIMO setup, specific drives need to be used in phase or out of phase (or set to zero) to create this uniaxial motion. The goal is to move the test article in a simple, prescribed way well below its first elastic modes so the responses of in-axis gauges can easily be compared to verify the local sensor orientation is correct. Correct any gauge orientation issues in the channel table and test geometry then complete a final set of rigid body checks to verify everything is correct before proceeding.

Note that most test setups will not have pure rigid body modes in the test coordinate system. For example, it is common to see a rigid body mode with some rotation motion that is superimposed on the primary translating motion. It is easy to identify this kind of motion as rigid when evaluating the operating deflection shapes from the rigid body check but can be very difficult to identify when just evaluating the time data or frequency spectra. As such it is suggested that the rigid body checks be done through inspection of the operating deflection shapes or metrics based on the operating deflection shapes.

Run System Identification Tests

System ID tests should be run at multiple levels to characterize the test system's dynamics and linearity. Start at a very low level, then use predictions to determine appropriate drive levels to achieve reasonable system ID test levels. At SNL, it is common to run system ID tests at low, medium, and high levels that are spread 6 dB apart. Ensure the high-level system ID test responses are between -12 and -6 dB below the test specification levels so the system ID data is similar to, but not above, the desired full test level. Process the responses after each system ID test and check data quality metrics.

Sometimes it is necessary to use shaped spectra to ensure good data quality (high SNR, linearity, coherence) while keeping levels below the test specification. This may require tailoring drive signals to be more low-frequency or high-frequency dominant.

When running a 6DOF test or any test using drive transformations in the control, it may be useful to perform system ID checks with untransformed drives as well as transformed drives. The transformations will produce different results as the drives are working together differently with or without a drive transformation. The resulting FRFs will be different as well. In general, if a drive transformation will be used in the test, use the same drive transformation in the system ID tests.

In addition to data quality checks, it is useful to plot example FRFs and condition numbers to understand system mode frequencies and system rank. Verify and document data quality for every system ID test. We recommend locking in an appropriate system ID test level for the duration of testing (determine it during pre-testing, then use the exact same method for all subsequent system ID tests to help with state of health and system change assessments).

Run Low Level Tests

It is recommended to run tests at multiple levels from low level to full level at increments of 3 or 6 dB to verify control accuracy and test quality. For example, low-level tests may be run at -12 dB and -6 dB prior to running at full level (0 dB). Run each test one at a time, checking data quality and test vs. specification comparisons for each test before proceeding to the next. Adjust controller settings as needed between tests and document how each test was run in the run log. Ensure there is ample headroom in the drives, amplifiers, and shakers to achieve the full test level; adjust settings as needed. Note that the low-level tests should be prescribed in the test matrix and agreed upon by the test stakeholders, since additional test time may be unacceptable in some scenarios.

Run the Full Level Test

With settings determined by low level tests, run the full level test. Process the full level test data and do data quality checks. Do initial test vs. specification comparisons and determine if adequate control accuracy was achieved. Do not re-run the full level test unless allowed by the test lead (undue hardware damage could occur from running at high levels for additional durations).

Post-test System Identification

At the end of the test series, run a post-test system ID test to verify the system state of health and compare vs. prior system ID tests. Document any changes in the system pre- vs. post-test in the test documentation and inform stakeholders. Ensure the run log is fully completed, with no empty spaces, and reflects what was done and how each test was performed. Note any changes or omissions to the test matrix.

Test Anomalies

All the test stakeholders should be consulted in the case of a test anomaly (poor control, something breaks, etc.). The test lead and customer should determine how to proceed.

End of Day and End of Test: Compile Data Packages and Document Progress

At the end of each test day, take time to compile data packages and document test progress for the day. Doing this regularly will ensure details do not get missed or forgotten. Update test notes and the test run log to ensure they are accurate and reflect what was done and how each test was performed. Note any anomalies or issues.

After all tests are complete, organize test data files, ensuring a consistent naming convention was used. If test data files are compiled with other data (for example photos, test geometries, processed data, etc.) into test data packages, ensure those are consistent and complete. Archive the run log, channel table, test matrix, and test data files/packages to ensure there is a backup copy of each. Share data with stakeholders as needed.

Post-Processing and Close Out

After testing is complete, move on to the post-processing phase where in-depth data analysis and documentation can occur. Initial results were obtained and reviewed during testing, but further analysis may be needed to more completely understand the test results. Analyses and QOIs should be agreed to during test planning.

One option is to compare various runs to understand the effects of controller settings or test levels on results. This would entail plotting data from multiple tests together and comparing vs. themselves or the test specification. Document observations from these comparisons and try to assess how controller or test settings affected results.

Create the final data analysis report, which is a comprehensive collection of processed test data. Often, this includes data quality checks and test vs. spec comparisons for each test. It may also include test vs. test and test vs. prediction comparisons, as well as other QOIs that are impractical to implement during day-of or quick look data analysis.

The final test setup should also be compared to the initial test setup (from Section 4.5). It is common to make small changes during a test, such as fixing a sensor orientation, and these changes should be properly documented.

Best Practices

The previous sections outlined a comprehensive MIMO testing procedure which, while thorough and time consuming, should result in high-quality test results. Following each step in the procedure is useful, but it is helpful to highlight some key focus areas which often make or break a MIMO test.

Instrumentation and Test Geometry

Getting instrumentation exactly right and documenting the as-instrumented test geometry is critical for MIMO to work properly and to make an accurate test record. Bookkeeping and consistent practices play a big role in reducing instrumentation errors. First, choose a convention for global (system), local, and gauge coordinate systems. Understand how to transform between each of these coordinate systems. Typical practice is to have the local and gauge coordinate system transformation handled by simply re-labeling the gauge axis to the local coordinate system in the channel table (e.g., the gauge axis is X+ but that is pointing in local Y-, so call that measurement Y-). Then, a transformation matrix can be used to convert from the local to the global systems (or vice versa). Next, to minimize bookkeeping, keep consistent with how gauges are installed (e.g., gauge Z+ is up, away from the mounting surface) and how channels are ordered in the channel table (e.g., each triax is plugged in in X, Y, Z gauge order).

Whenever possible, make an accurate test geometry which captures the location and direction of the as-measured channels. This test geometry can be used to determine if gauges are installed correctly using rigid body checks and is useful for understanding system motion using operational deflection shape analysis. Most importantly, the test geometry is a visual record of the test configuration. If exact locations or directions are not known, approximations can still be useful.

Understanding System FRFs, Conditioning and Rank

System ID measurements are used throughout MIMO test series to estimate the system output/input transfer functions (or FRFs) for use in MIMO control, but the same data and FRFs are very helpful for understanding the system dynamics, conditioning and effective rank. The condition number and rank of the FRF matrix is critical for determining appropriate transformations and regularization schemes to use in MIMO control. Always compute and plot the condition numbers (ratio of the biggest to smallest singular values) to determine the system rank as a function of frequency as this will tell you the number of active modes and how to appropriately regularize the system. It can also be useful to explicitly review the singular values of the FRF matrix to understand the number of "independent" inputs that are acting on the system.

Optimizing Controller Settings

Many MIMO tests are sensitive to controller settings. The test operators should be familiar with various controller settings and methods such as: closed-loop control methods, input and output transformations, regularization, and weighting. Each of these settings affects test behavior for both inputs and outputs and should be chosen thoughtfully and carefully. Consider which settings to choose based on the test type, and then refine those settings based on low-level tests and pre-test predictions. For example, a 6DOF test will often utilize an input (drive) transformation, which may then be augmented with regularization. To dial-in control accuracy at DOFs of interest, a weighting scheme could be used.

Day-of Data Analysis and Data Quality Checks

It is imperative that test operators analyze test results and understand what has happened in each run. This is for two reasons: first, to verify data quality (do I trust this measurement?) and second, to understand the test results (did this test meet objectives?). If test data is not examined in near real time, it is not possible to optimize settings or determine if test objectives are being met; you are flying blind. Tools and workflows to analyze data and perform test and data quality checks should be developed and available to support day-of data analyses.

Documentation

Thorough notes and documentation are critical to keeping track of various methods, settings and results. With each MIMO test, there can be dozens of parameters to document so the test operators must capture all this important information in a comprehensive run log. While many of these settings may be captured in data files, the operators should interpret this information and record it in the run log, so it is human readable and actionable for future runs or future tests.

Keep up with documentation, recording information about each run immediately and noting test performance, anomalies, and settings. It can be helpful to document the test two ways: first, the run log which captures each run and its settings and second, with a set of notes which is the "story" of the test day, focused more on what and why than a specific set of details.

Two-person Test Execution

MIMO vibration test execution is a complicated activity and can be overwhelming activity for a single person to undertake. Consequently, a two-person framework with clear roles and responsibilities is suggested to maximize test efficiency and quality. An example of the roles in a two-person framework is:

- Test Operator: The test operator is responsible for the activities related to running the test, such as: operating the control and data acquisition software, monitoring shaker performance, etc.
- Test Documenter: The test documenter is responsible for ensuring that the test matrix is being followed and that the appropriate information is entered into the run log.

Note that the roles in the two-person testing framework can change depending on the skillsets of performing the test. However, each person show have a clear role that covers the different tasks for the activities that were described in Section 5. Ideally, the roles should be defined such that each person can focus on a single task at any one-time during test execution. A secondary benefit of two-person testing is that it ensures a second person is always available for peer review and consultation during test execution.

Conclusions

Proliferation of MIMO vibration tests for research, development, and qualification activities requires test labs demonstrate a history of consistent, high-quality tests. An important step in that direction is formalizing and documenting processes, and this paper aims to be a useful starting point for MIMO testing procedures for various laboratories. This procedure is written and organized to ensure that test activities meet customer goals: run the required tests using an appropriate test setup and guarantee the data is reliable. Each step is designed to guarantee that a test is carefully planned, comprehensively documented, correctly executed, and yields dependable data. When carried out according to the procedure, the test should fulfill the customer's objectives.

Acknowledgments This procedure is the result of more than a decade of MIMO R&D and applied work from many contributors across Sandia National Laboratories, in addition to many more years of experience in single-axis vibration testing, modal testing, and related structural dynamics work.

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Appendix A

Below is an example test matrix for a random vibration 6DOF test which includes various runs in the setup and troubleshooting phase, two runs in the low-level test phase, one full-level test and a post-test system identification run. The test series is divided into different phases with checkpoints (highlighted blue) to instruct the test team to pause and check specific data or results before proceeding. The test matrix can also serve as the basis for a run log by including fields to note test anomalies, file names, and other relevant information.

Table 1 Example test matrix

Phase	Complete ?	Date	File Name	Test Description	Spec Description	Test Level (dB)	Frequency Range (Hz)	Duration (s)	MIMO Control Settings & Transformations
Setup & Trouble-shooting			run001_pretest	Check amp to shaker connection: run each shaker one at a time	N/A	N/A	N/A	30	N/A
			run002_noise_floor	Preliminary noise floor	N/A	N/A	N/A	30	N/A
			Pause: Verify shaker drives, note noise issues and fix bad channels						
			run003_rigid_body	Rigid body check: X	N/A	0.10 V-pk	20 Hz	10	6DOF kinematic drive transformation
			run004_rigid_body	Rigid body check: Y	N/A	0.10 V-pk	20 Hz	10	6DOF kinematic drive transformation
			run005_rigid_body	Rigid body check: Z	N/A	0.10 V-pk	20 Hz	10	6DOF kinematic drive transformation
			run006_rigid_body	Rigid body check: RX	N/A	0.10 V-pk	20 Hz	10	6DOF kinematic drive transformation
			run007_rigid_body	Rigid body check: RY	N/A	0.10 V-pk	20 Hz	10	6DOF kinematic drive transformation
			run008_rigid_body	Rigid body check: RZ	N/A	0.10 V-pk	20 Hz	10	6DOF kinematic drive transformation
			Pause: Check rigidy body test results and verify gauge orientations. Fix test geometry and re-run as needed						
			run009_system_id	Preliminary system ID, low level	N/A	0.10 V-RMS	20-4000 Hz	60	6DOF kinematic drive transformation
			run010_system_id	Preliminary system ID, medium level	N/A	0.20 V-RMS	20-4000 Hz	60	6DOF kinematic drive transformation
			run011_system_id	Preliminary system ID, high level	N/A	0.40 V-RMS	20-4000 Hz	60	6DOF kinematic drive transformation
			Pause: Compare system ID results to understand linearity, necessary amplifier gain, and required system ID levels. Run additional system ID at desired system ID level						
Low Level Tests			run012_system_id	System ID before random vibe tests	N/A	0.20 V-RMS	20-4000 Hz	60	6DOF kinematic drive transformation
			run013_random_vibe	Low level test, -12 dB	6DOF virtual point translated to table gauges	-12 dB	50-2000 Hz	30	condition number threshold of 500. 6DOF kinematic drive transformation
			run014_random_vibe	Low level test, -6 dB	6DOF virtual point translated to table gauges	-6 dB	50-2000 Hz	30	condition number threshold of 500. 6DOF kinematic drive transformation
			Pause: Check control accuracy, adjust control settings and re-run as needed						
Full Level Test			run015_random_vibe	Full level test, 0 dB	6DOF virtual point translated to table gauges	0 dB	50-2000 Hz	30	condition number threshold of 500. 6DOF kinematic drive transformation
			Pause: Check control accuracy and note test performance						
Post Test			run016_noise_floor	Post-test noise floor	N/A	N/A	N/A	30	N/A
			run017_system_id	System ID before random vibe tests	N/A	0.20 V-RMS	20-4000 Hz	60	6DOF kinematic drive transformation
			Pause: Compare pre- and post-test noise floor and system ID results to verify the system did not change and sensors are healthy						